NATIONAL BUREAU OF STANDARDS REPORT

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SPECTROPHOTOMETRIC AND COLORIMETRIC

STUDY OF DISEASED

AND RUST RESISTING CEREAL CROPS

By

Harry J. Keegan,

John C. Schleter,

Wiley A. Hall, Jr.,

and

Gladys M. Haas

To

U. S. Department of the Air Force
Aerial Reconnaissance Laboratory
Wright Air Development Center
Wright-Patterson Air Force Base, Ohio

NBS

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NATIONAL BUREAU OF STANDARDS REPORT

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Photometry and Colorimetry Section
Optics and Metrology Division

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NATIONAL BUREAU OF STANDARDS

PREFACE

This is one of a series of NBS reports of spectrophotometric and colorimetric work done under NBS Project No. 0201-20-2325 entitled Color Reconnaissance Studies, financed by the Aerial Reconnaissance Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio; Air Force Contract No. 33(616) 52-21. The present report on cereal crop diseases was made in cooperation with the National Research Council, Committee on Plant and Crop Ecology, Division of Biology and Agriculture, Dr. Everett F. Davis, Executive Secretary; and with its Sub-committee on Crop Geography and Vegetation Analysis, under the chairmanship of Dr. Robert N. Colwell, Associate Professor of Forestry and Associate Silviculturist in the Experiment Station, Department of Forestry, University of California, Berkeley, California.

Harry J. Keegan
Project Leader

SPECTROPHOTOMETRIC AND COLORIMETRIC STUDY OF DISEASED AND RUST RESISTING CEREAL CROPS

Harry J. Keegan, John C. Schleter, Wiley A. Hall, Jr., and Gladys M. Haas *

Abstract

This study involves the development of a method for the detection and for the evaluation of wheat rust and of other cereal crop diseases in the field by means of ground or aerial photography based on spectrophotometric and colorimetric analyses of specimens of healthy and diseased cereal crops.

To develop this method, measurements of the visible and the near infrared spectral directional reflectance, or spectral transmittance, of 30 specimens of diseased and non-diseased cereal crop plants and of 6 specimens of rust were made on a General Electric recording spectrophotometer for the spectral range 400 to 1080 millimicrons. Three of the samples of rust were measured for spectral transmittance and three for spectral directional reflectance. All of the 30 specimens of diseased and rust resisting cereal crop plants were measured for spectral directional reflectance; 14 specimens, of which nine were young wheat plants, two mature heads of wheat, and three young rye plants were grown in pots under controlled conditions at the Plant Industry Station, USDA, Beltsville, Maryland; the remaining 16 were the leaves, heads, and stalks of three species of wheat grown in the field at Stillwater, Oklahoma, and flown to Washington, D. C. for measurement at the National Bureau of Standards.

These spectrophotometric measurements have been illustrated and tables of data are included as well as graphs and tables of chromaticity coordinates, dominant wavelength, excitation purity, daylight reflectance, Munsell renotations, and ISCC-NBS (Inter-Society Color Council - National Bureau of Standards) color designations. In addition, color difference determinations in terms of the NBS unit of color difference have been made between the same parts of different plants and between diseased and non-diseased parts of the same plants.

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* Miss Haas is at present employed at the Mare Island Naval Shipyard, San Francisco, California.

Contents

I. Introduction

The overall objective of this Air Force investigation is stated as follows: "To develop by visible, near infrared, and near ultraviolet spectrophotometry, methods for the detection of objects from color reconnaissance; to study the colors, tonal contrast, and color separation necessary in aerial photography to yield maximum information; to determine the wavelength region at which the film manufacturer should strive to obtain maximum sensitivity to yield clear separation of an object from its adjacent area rather than to yield true color fidelity; to determine the characteristics required in a sensitized material for the rapid and accurate extraction of this information".

The present report results from work that began prior to the formulation of the objective of the Air Force investigation as stated above but which carried over beyond July 1, 1952 when the WADC-financed NBS Color Reconnaissance Studies project began. In April, 1952, the Committee on Plant and Crop Ecology of the National Research Council, Dr. E. F. Davis, Executive Secretary, invited the senior author to attend a conference to assist in the development of methods for the detection of wheat rust in a field of growing wheat. With the approval of the Director of the National Bureau of Standards, arrangements were made to perform preliminary spectrophotometric determinations on controlled specimens of rust-resisting young wheat plants and susceptible young wheat plants that had been manually inoculated with wheat rust. The results of these initial determinations appeared promising and further preliminary investigations were made resulting in the recommendations of the present method. The pertinent events leading to this investigation are listed in chronological order in Appendix E of this report (page 126). In 1954, the Air Force became interested in these studies and the present report is made possible by their support of this work.

To develop fully this method for the detection of wheat rust in a field of growing wheat it was necessary to measure the spectral directional reflectance for the visible and near infrared spectrum, 400 to 1080 millimicrons of a number of specimens of the ventral sides of leaves of young wheat plants that had been manually inoculated and of similar species of rust-resisting plants. Measurements were also made of potted plants that had been maintained with low and with excessive water; of wheat rusts for both spectral transmittance and spectral directional reflectance; of the inoculated heads of susceptible and resisting wheat plants; of the leaves of diseased and healthy rye plants; and of leaves, stalks, and heads of three species of field grown wheat.

Illustrations were prepared showing the results of these visible and near infrared spectral directional reflectance and spectral transmittance measurements, and computations were made from the visible spectral data of these 36 specimens to illustrate their colorimetric properties in terms of the CIE standard observer and coordinate system chromaticity coordinates and daylight reflectances, as well as in terms of the Munsell renotation color

system, the ISCC-NBS system of color designations, and in terms of the NBS unit of color difference.

It is believed that this type of information is a necessary step in the development of methods for the aerial detection and evaluation of wheat rust or of other types of cereal crop diseases.

The method of measurement and computation used in this report is that requested in the original project proposal quoted above and used in four of the previous seven reports issued under this project. [1, 2, 3, 4] *

II. Material

The specimens measured in these determinations are of five types: (a) young wheat plants grown in pots under controlled conditions, (b) mature wheat plants grown under controlled conditions, (c) specimens of spores from plants grown under controlled conditions, (d) young rye plants grown in pots under controlled conditions, and (e) mature wheat plants grown in the field.

The specimens grown under controlled conditions ((a), (b), and (c) above) were produced at the USDA Plant Industry Station at Beltsville, Maryland, and brought to the NBS for measurements by Dr. H. A. Rodenhiser of the Beltsville Station. These specimens are further identified in Table I (page 42) Specimen Numbers 1 to 17.

The specimens of young rye plants grown under controlled conditions ((d) above) were presumably grown at Beltsville, Maryland, and were brought to the NBS for measurements by Dr. Robert N. Colwell. These specimens are further identified in Table I, Specimen Numbers 18 to 20.

The mature wheat plants grown in the field ((e) above) were delivered to the NBS for measurement by Dr. Colwell, who had the specimens flown to Washington, D. C. from the USDA, Plant Industry Station, located at Stillwater, Oklahoma. These specimens are further identified in Table V (page 97) Specimen Numbers 21 to 36.

The specimen designations used in this report are those given by either Dr. Colwell or Dr. Rodenhiser.

III. Preparation of Specimens

In order to study the spectrophotometric properties of the specimen plants, it was necessary to cut from these plants sections of leaves, stalks, and heads. The size of these cut specimens was such that it was necessary to form composite samples made from several pieces of the same or similar parts of the plant. In the case of the leaves and stalks, each sample to be measured consisted of four or five lengths of specimen mounted between clear

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* Numbers in brackets refer to bibliography on page 124 of this report.

microscope cover glasses. The heads of the plants were placed in a clear glass cell ordinarily used for the measurement of spectral transmittance of solutions, using enough heads to fill the cell. The spore specimens ((c) above), like the leaves and stalks, were placed between clear microscope cover glasses. The spore specimens prepared for the measurement of spectral transmittance of the spore consisted of a thin layer of specimen; the specimens of spore for the spectral directional reflectance measurements consisted of a thick layer of specimen.

When mounted in the spectrophotometer for measurement of spectral directional reflectance, all of the composite specimens between microscope cover glasses and in the glass cell were backed with black velvet on a wooden block.

IV. Spectrophotometric Measurements

Measurements of spectral directional reflectance for the visible and near infrared spectral ranges (400 to 1080 millimicrons) were made for 33 specimens on a General Electric recording spectrophotometer [5, 6]. Similar measurements of spectral transmittance were also made on three specimens of spore.

The measurements of spectral directional reflectance were made for the condition of included specular component of the reflected radiant energy. Slits of approximately 10 millimicrons of spectral width were used for the measurements in the visible spectrum, 400 to 750 millimicrons, and 20 millimicrons of spectral width for the near infrared spectrum, 730 to 1080 millimicrons.

V. Spectrophotometric Results

The results of the spectrophotometric measurements of spectral directional reflectance or spectral transmittance of this report are shown on the 22 Ozalid copies of the original recordings from the General Electric recording spectrophotometer. These Ozalid copies are a part of Appendices A and C of this report; eleven of them are the visible spectrum, 400 to 750 millimicrons, and eleven of them are for the near infrared spectrum, 730 to 1080 millimicrons.

Values of spectral directional reflectance or spectral transmittance were read at 10 millimicron intervals from 400 to 1080 millimicrons for each of the 72 determinations made on the 36 specimens. These 72 sets of spectrophotometric data are listed in Appendices B and D. Forty of these 72 sets of spectrophotometric data for the controlled wheat, rye, and spore specimens grown at Beltsville, Maryland, are illustrated in Figures 1, 2, 3, 4, 9, 10, and 15. The remaining 32 sets of spectrophotometric data for the field grown wheat specimens from Stillwater, Oklahoma, are illustrated in Figures 18, 19, 20, 21, 22, 23, 24, and 25.

VI. Colorimetric Computations

The spectral-directional-reflectance or spectral-transmittance data of each of the 36 specimens listed in Appendices B and D for the visible spectrum (400 to 750 millimicrons) were converted into terms of luminous reflectance or luminous transmittance, Y, and chromaticity coordinates, x and y, of the C.I.E. colorimetric system by integration according to the C.I.E. standard observer [7] for C.I.E. source C, representative of average daylight. In addition to the chromaticity coordinates, x and y, the dominant wavelength, Λ, and excitation purity, p, of each of the 36 specimens have been derived.

Dominant wavelength and excitation purity are alternative specifications, more or less suggestive of the appearance of the color and help to form a chromaticity specification sometimes more easily understood than the chromaticity coordinates, x and y. Dominant wavelength is defined as the wavelength corresponding to the intersection with the spectrum locus in the C.I.E. diagram of a straight line drawn through the neutral point (Source C), and the sample point. Excitation purity is defined as the ratio of the distance, in the C.I.E. diagram, between the neutral point and the sample point to the distance between the neutral point and the point on the spectrum locus representing the dominant wavelength of the specimen. Dominant wavelength thus indicates what part of the spectrum has to be mixed with the neutral standard to produce the unknown color, and the excitation purity indicates the degree of approach of the unknown color to the spectrum color so defined. The dominant wavelength and excitation purity of the specimens of this report were determined from chromaticity data by means of graphs showing the conversion of C.I.E. chromaticity data into these terms [8].

The chromaticity coordinates, daylight reflectance or daylight transmittance, dominant wavelength, and excitation purity are listed in Tables II and VI and in illustrations of segments of the C.I.E. chromaticity diagram at the end of each of the two type classifications of this report; namely specimens grown in pots under controlled conditions (Figures 5, 6, 11, 12, and 16) at Beltsville, Maryland, and field-grown specimens (Figures 26, 27, and 28) from Stillwater, Oklahoma.

VII. Munsell Renotations and ISCC-NBS Color Designations

From the above-mentioned determinations of C.I.E. chromaticity coordinates and daylight reflectances or daylight transmittances of the 36 specimens studied in this report, the Munsell renotations (H V/C) were obtained from graphs of conversion from the C.I.E. system to the Munsell renotation system [9]. These Munsell renotations were then converted into terms of the ISCC-NBS (Inter-Society Color Council - National Bureau of Standards) color designations [10]. Similarly, these renotations and color designations are listed in Tables III and VII and illustrated (Figures 7, 8, 13, 14, 17, 29, 30, and 31) in graphs under the respective type classifications.

VIII. Color Difference Computations

From the Munsell renotations of the 36 specimens, color differences in terms of the NBS unit of color difference (ΔE) were computed by means of the Godlove formula [11] , as follows:

$$\Delta E_{NBS} = 5 \left[2C_1C_2\phi(H) + (\Delta C)^2 + (4\Delta V)^2 \right]^{1/2},$$

where $\phi(H) = 1 - \cos 3.6\Delta H$, and ΔH, ΔV, and ΔC refer to differences in Munsell hue, value, and chroma, respectively.

These color differences were computed between diseased and non-diseased parts of the similar plants, between plants having excessive and low water content, and between the specimens of spores. These results are listed in Tables IV and VIII under the respective type classifications.

IX. Specimens Grown Under Controlled Conditions at Beltsville, Maryland

All of the 20 specimens grown under controlled conditions at the USDA Plant Industry Station, Beltsville, Maryland, are considered in this part of this report. Seventeen of them, wheat plants growing in pots, were brought to the NBS for measurement by Dr. H. A. Rodenhiser. The three rye specimens, two potted and one unpotted, were brought to the NBS for measurement by Dr. R. N. Colwell. The specimen designations given by Dr. Rodenhiser or by Dr. Colwell, together with the specimen numbers arbitrarily assigned and used throughout this section of this report, are listed in Table I (page 42).

Figures 1, 2, 3, 4, 9, 10, and 15 show spectral directional reflectance curves or spectral transmittance curves of the specimens designated in the legends of the illustrations. The data used for these illustrations are taken from those shown in Appendix A and listed in Appendix B.

The chromaticity coordinates, dominant wavelength, and excitation purity of the specimens of these seven illustrations are shown in segments of the C.I.E. chromaticity diagram, for Source C, in Figures 5, 6, 11, 12, and 16. The data used for these illustrations are listed in Table II. Table II also lists the daylight reflectance or daylight transmittance of these 20 specimens.

The Munsell renotations of these same specimens are illustrated in the schematic diagrams of the "Ideal Munsell System" in Figures 7, 8, 13, 14, and 17. The data used for these illustrations are listed in Table III together with the corresponding ISCC-NBS color designations.

Determinations were made of color difference between the related specimens indicated in Table IV.

Figure 1. Visible and near infrared spectral directional reflectance of the leaves of five specimens of young wheat plants:

(1) Leaves of SUWON 92, sprayed and inoculated

(2) Leaves of SUWON 92, sprayed

(3) Leaves of LEE, natural

(4) Leaves of wheat, inoculated (species undesignated)

(9) Leaves of wheat, inoculated (species undesignated)

Figure 2. Visible and near infrared spectral directional reflectance of the leaves of two specimens of young wheat plants:

(5) Leaves of L. C. Susceptible, inoculated (excessive water)

(6) Leaves of L. C. 15B Susceptible, inoculated (low water)

Figure 3. Visible and near infrared spectral directional reflectance of the leaves of two specimens of young wheat plants:

(7) Middle leaves, 127-36-L Resistant, (low water)

(8) Top leaves, 127-17-L Resistant, (excessive water)

Figure 4. Visible and near infrared spectral directional reflectance of the heads (fruit) of two specimens of mature wheat plants:

(10) Mature heads (fruit), Resisting 36 4-16-52; 5-36-L, inoculated

(11) Mature heads (fruit), LC 10/19; 38 4-23-52, inoculated

Figure 5. Segment of the C.I.E. chromaticity diagram showing dominant wavelength, excitation purity, and chromaticity coordinates, for Source C, of the leaves of five specimens of young wheat plants:

(1) Leaves of SUWON 92, sprayed and inoculated

(2) Leaves of SUWON 92, sprayed

(3) Leaves of LEE, natural

(4) Leaves of wheat, inoculated (species undesignated)

(9) Leaves of wheat, inoculated (species undesignated)

and of the heads (fruit) of two mature wheat plants:

(10) Mature heads (fruit), Resisting 36 4-16-52; 5-36-L, inoculated

(11) Mature heads (fruit), LC 10/19; 38 4-23-52, inoculated

Figure 6. Segment of the C.I.E. chromaticity diagram showing dominant wavelength, excitation purity, and chromaticity coordinates, for Source C, of the leaves of four specimens of young wheat plants:

(5) Leaves of L. C. Susceptible, inoculated (excessive water)

(6) Leaves of L. C. 15B Susceptible, inoculated (low water)

(7) Middle leaves, 127-36-L, Resistant, (low water)

(8) Top leaves, 127-17-L Resistant, (excessive water)

Figure 7. Schematic illustration of the vertical and horizontal projections of the "ideal" Munsell system showing the Munsell Value (upper diagram) plotted against the Munsell Hue and Chroma points projected from the lower diagram of the leaves of five specimens of young wheat plants:

(1) Leaves of SUWON 92, sprayed and inoculated

(2) Leaves of SUWON 92, sprayed

(3) Leaves of LEE, natural

(4) Leaves of wheat, inoculated (species undesignated)

(9) Leaves of wheat, inoculated (species undesignated)

and of the heads (fruit) of two mature wheat plants:

(10) Mature heads (fruit), Resisting 36 4-16-52; 5-36-L, inoculated

(11) Mature heads (fruit), LC 10/19; 38 4-23-52, inoculated

Figure 8. Schematic illustration of the vertical and horizontal projections of the "ideal" Munsell system showing the Munsell Value (upper diagram) plotted against the Munsell Hue and Chroma points projected from the lower diagram of the leaves of four specimens of young wheat plants:

(5) Leaves of L. C. Susceptible, inoculated (excessive water)

(6) Leaves of L. C. 15B Susceptible, inoculated (low water)

(7) Middle leaves, 127-36-L Resistant, (low water)

(8) Top leaves, 127-17-L Resistant, (excessive water)

Figure 9. Visible and near infrared spectral directional reflectance of three specimens of wheat rust:

(12) Pure spore

(13) Pure leaf rust

(14) Pure stem rust

Figure 10. Visible and near infrared spectral transmittance of three specimens of wheat rust:

(15) Pure spore 15B 5/13/52

(16) Pure leaf rust

(17) Pure stem rust

Figure 11. Segment of the C.I.E. chromaticity diagram showing dominant wavelength, excitation purity, and chromaticity coordinates, for Source C, of three specimens of wheat rust, obtained from spectral directional reflectance data:

(12) Pure spore

(13) Pure leaf rust

(14) Pure stem rust

Figure 12. Segment of the C.I.E. chromaticity diagram showing dominant wavelength, excitation purity, and chromaticity coordinates, for Source C, of three specimens of wheat rust, obtained from spectral transmittance data:

(15) Pure spore 15B 5/13/52

(16) Pure leaf rust

(17) Pure stem rust

Figure 13. Schematic illustration of the vertical and horizontal projections of the "ideal" Munsell system showing the Munsell Value (upper diagram) plotted against the Munsell Hue and Chroma points projected from the lower diagram of three specimens of wheat rust, obtained from spectral directional reflectance data:

(12) Pure spore

(13) Pure leaf rust

(14) Pure stem rust

Figure 14. Schematic illustration of the vertical and horizontal projections of the "ideal" Munsell system showing the Munsell Value (upper diagram) plotted against the Munsell Hue and Chroma points projected from the lower diagram of three specimens of wheat rust, obtained from spectral transmittance data:

(15) Pure spore 15B 5/13/52

(16) Pure leaf rust

(17) Pure stem rust

Figure 15. Visible and near infrared spectral directional reflectance of the leaves of three specimens of young rye plants:

(18) Leaves of rye, diseased

(19) Leaves of rye, non-diseased

(20) Leaves of rye (unpotted plant)

Figure 16. Segment of the C.I.E. chromaticity diagram showing dominant wavelength, excitation purity, and chromaticity coordinates, for Source C, of the leaves of three specimens of young rye plants:

(18) Leaves of rye, diseased

(19) Leaves of rye, non-diseased

(20) Leaves of rye (unpotted plant)

Figure 17. Schematic illustration of the vertical and horizontal projections of the "ideal" Munsell system showing the Munsell Value (upper diagram) plotted against the Munsell Hue and Chroma points projected from the lower diagram of the leaves of three specimens of young rye plants:

(18) Leaves of rye, diseased

(19) Leaves of rye, non-diseased

(20) Leaves of rye (unpotted plant)

Table I

List of the specimens raised at the U.S.D.A. Plant Industry Station at Beltsville, Maryland, and brought to the NBS by Dr. Rodenhiser.

Object No.	Specimen Designations
	Diseased and Rust Resisting Wheat Leaves
(1)	Leaves of SUWON 92, Sprayed and Inoculated
(2)	Leaves of SUWON 92, Sprayed
(3)	Leaves of LEE, Natural
(4)	Leaves of Wheat, Inoculated (species undesignated)
(5)	Leaves of L. C. Susceptible, Inoculated (excessive water)
(6)	Leaves of L. C. 15 B Susceptible, Inoculated (low water)
(7)	Middle Leaves, 127-36-L Resistant (low water)
(8)	Top Leaves, 127-17-L Resistant (excessive water)
(9)	Leaves of Wheat, Inoculated (species undesignated)
	Inoculated Heads of Susceptible and Resisting Wheat
(10)	Mature Heads (fruit), Resisting 36 4-16-52; 5-36-L, Inocula
(11)	Mature Heads (fruit), LC 10/19; 38 4-23-52, Inoculated
	Wheat Spore (reflectance)
(12)	Pure Spore (reflectance)
(13)	Pure Leaf Rust (reflectance)
(14)	Pure Stem Rust (reflectance)
	Wheat Spore (transmittance)
(15)	Pure Spore 15B 5/13/52 (transmittance)
(16)	Pure Leaf Rust (transmittance)
(17)	Pure Stem Rust (transmittance)
	Diseased and Rust Resisting Rye
(18)	Leaves of Rye, Diseased
(19)	Leaves of Rye, Non-diseased
(20)	Leaves of Rye (unpotted plant)

Table II

Specimens from Beltsville, Maryland

Chromaticity Coordinates, Daylight Reflectances, Dominant Wavelength and Excitation Purity for C.I.E. Source C of the Specimens Studied.

Specimen Number	Chromaticity Coordinates x	Chromaticity Coordinates y	Daylight Reflectance Y(%)	Dominant Wavelength (mμ)	Excitation Purity (%)
(1)	0.353	0.362	18.3	576.7	23.6
(2)	.322	.358	17.2	562.6	14.4
(3)	.326	.365	19.2	564.0	17.4
(4)	.411	.384	8.8	583.4	45.1
(5)	.354	.374	8.4	574.0	27.2
(6)	.397	.409	10.3	576.5	48.0
(7)	.340	.406	12.2	564.1	32.0
(8)	.316	.363	7.9	557.0	14.1
(9)	.368	.372	21.9	578.1	30.4
(10)	.355	.356	44.6	579.2	22.8
(11)	.358	.353	36.5	581.4	22.6
(12)	.462	.388	6.6	588.0	60.0
(13)	.391	.348	14.4	590.4	30.0
(14)	.373	.347	15.9	587.6	25.0
(15)	.338	.315	0.3*	625.	6.9
(16)	.499	.420	5.3*	586.0	78.3
(17)	.412	.361	0.8*	589.0	39.4
(18)	.348	.376	23.1	571.5	26.1
(19)	.320	.359	19.2	561.0	14.1
(20)	.322	.366	16.2	561.2	16.7

*Daylight transmittance, Y(%).

Table III

Specimens from Beltsville, Maryland

Munsell Renotations and ISCC-NBS Color Designations of the Specimens Studied.

Specimen Number	Munsell Renotation	ISCC-NBS Color Designation
(1)	4.2Y 4.8/2.0	Light grayish olive
(2)	6.6GY 4.7/2.0	Grayish yellow green
(3)	6.1GY 4.9/2.2	Grayish yellow green
(4)	9.3YR 3.4/3.4	Dark yellowish brown
(5)	8.5Y 3.4/1.9	Grayish olive
(6)	5.0Y 3.7/3.5	Moderate olive
(7)	5.8GY 4.0/3.4	Moderate olive green
(8)	8.2GY 3.3/2.1	Dark grayish green
(9)	2.7Y 5.2/2.9	Light olive brown
(10)	0.6Y 7.1/2.7	Light grayish yellowish brown
(11)	9.1YR 6.5/2.7	Light grayish yellowish brown
(12)	6.3YR 3.0/4.9	Moderate brown
(13)	2.8YR 4.3/3.4	Moderate reddish brown
(14)	4.5YR 4.5/2.7	Light grayish reddish brown
(15)	N 0.2/	Black
(16)	8.4YR 2.7/5.9	Deep yellowish brown
(17)	N 0.7/	Black
(18)	0.5GY 5.4/2.5	Light grayish olive
(19)	7.2GY 4.9/2.1	Grayish yellow green
(20)	6.9GY 4.6/2.3	Grayish yellow green

Table IV

Specimens from Beltsville, Maryland

Color Differences Computed from the Godlove Color-Difference Formula Between the Specimens Indicated.

Color Difference Between Specimens Number: Reference	Comparison	Color Difference ΔE
(1)	(2)	7.9
(3)	(1)	8.0
(3)	(2)	4.1
(3)	(4)	33.6
(3)	(9)	12.4
(7)	(5)	15.3
(7)	(6)	13.0
(7)	(8)	15.6
(10)	(11)	12.1
(12)	(13)	27.4
(12)	(14)	32.0
(15)	(16)	58.1
(15)	(17)	10.0
(19)	(18)	11.3
(19)	(20)	6.1

Appendix A

Ozalid copies of the original recordings of spectral directional reflectance or of spectral transmittance of the 20 specimens of wheat or rye plants grown under controlled conditions at Beltsville, Md., and of spore made on a General Electric recording spectrophotometer.

Index to Appendix A

Specimen Number	GE Graph Sheet Serial Number: Visible Spectrum	GE Graph Sheet Serial Number: Near Infrared Spectrum	Curve Number	Date Measured
(1)	GE II- 964	GE II- 965	1	5- 7-52
(2)	- 964	- 965	2	5- 7-52
(3)	- 964	- 965	3	5- 7-52
(4)	- 969	- 970	4,5; and 4	5-15-52
(5)	- 972	- 971	1	5-16-52
(6)	- 972	- 971	2	5-16-52
(7)	- 972	- 971	3	5-16-52
(8)	- 972	- 971	4	5-16-52
(9)	- 986	- 987	1	6- 3-52
(10)	- 986	- 987	6	6- 3-52
(11)	- 986	- 987	7	6- 3-52
(12)	- 969	- 970	6; and 5	5-15-52
(13)	- 986	- 987	3	6- 3-52
(14)	- 986	- 987	5	6- 3-52
(15)	- 973	- 974	1	5-26-52
(16)	- 986	- 987	2	6- 3-52
(17)	- 987	- 987	4	6- 3-52
(18)	-1376	-1377	1	1-19-54
(19)	-1376	-1377	2	1-19-54
(20)	-1376	-1377	3	1-19-54

Appendix B

Tables of spectral data on the 20 specimens read from the spectrophotometric curves of Appendix A.

Diseased and Rust Resisting Wheat
(From Beltsville, Maryland)

Spectral Directional Reflectance of the Leaves of the Indicated Wheat Specimens for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix A; GE Graph Sheets Serial No. GE II-964 and 965)

(1) Leaves of SUWON 92				(2) Leaves of SUWON 92				(3) Leaves of LEE			
Sprayed and Inoculated				Sprayed				Natural			
Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.118	750	0.516	400	0.126	750	0.590	400	0.134	750	0.594
10	.120	60	.539	10	.128	60	.622	10	.136	60	.622
20	.122	70	.551	20	.130	70	.636	20	.136	70	.636
30	.122	80	.560	30	.130	80	.644	30	.136	80	.642
40	.120	90	.568	40	.129	90	.646	40	.136	90	.644
450	.120	800	.576	450	.130	800	.648	450	.136	800	.644
60	.120	10	.584	60	.130	10	.648	60	.136	10	.646
70	.120	20	.590	70	.129	20	.648	70	.136	20	.646
80	.120	30	.596	80	.128	30	.648	80	.136	30	.646
90	.124	40	.602	90	.128	40	.647	90	.136	40	.646
500	.126	850	.608	500	.130	850	.646	500	.140	850	.646
10	.131	60	.614	10	.139	60	.646	10	.152	60	.646
20	.146	70	.620	20	.159	70	.646	20	.176	70	.647
30	.172	80	.624	30	.186	80	.646	30	.207	80	.648
40	.192	90	.629	40	.202	90	.645	40	.225	90	.648
550	.204	900	.633	550	.206	900	.644	550	.230	900	.650
60	.208	10	.636	60	.204	10	.644	60	.229	10	.650
70	.205	20	.639	70	.190	20	.643	70	.214	20	.651
80	.198	30	.642	80	.174	30	.642	80	.194	30	.650
90	.195	40	.642	90	.162	40	.638	90	.182	40	.646
600	.195	950	.639	600	.156	950	.634	600	.175	950	.638
10	.195	60	.634	10	.151	60	.625	10	.170	60	.628
20	.194	70	.630	20	.144	70	.616	20	.160	70	.618
30	.194	80	.630	30	.140	80	.614	30	.156	80	.613
40	.194	90	.632	40	.136	90	.615	40	.152	90	.613
650	.190	1000	.634	650	.128	1000	.618	650	.140	1000	.616
60	.188	10	.640	60	.124	10	.622	60	.134	10	.622
70	.185	20	.646	70	.118	20	.627	70	.128	20	.627
80	.186	30	.651	80	.116	30	.632	80	.124	30	.632
90	.195	40	.656	90	.121	40	.636	90	.132	40	.636
700	.243	1050	.662	700	.169	1050	.639	700	.188	1050	.639
10	.307	60	.663	10	.250	60	.641	10	.275	60	.641
20	.372	70	.665	20	.344	70	.644	20	.366	70	.644
30	.438	80	.666	30	.449	80	.645	30	.465	80	.645
40	.486			40	.534			40	.542		

Diseased and Rust Resisting Wheat
(From Beltsville, Maryland)

Spectral Directional Reflectance of the Leaves of the Indicated Wheat Specimens for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix A; GE Graph Sheets Serial No. GE II-969, 970, 971, and 972.)

(4) Leaves of Wheat Inoculated (species undesignated)				(5) Leaves of L.C. Susceptible, Inoculated (excessive water)				(6) Leaves of L.C. 15B Susceptible, Inoculated (low water)			
Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.032	750	0.391	400	0.043	750	0.471	400	0.032	750	0.421
10	.035	60	.418	10	.047	60	.504	10	.035	60	.436
20	.037	70	.437	20	.050	70	.524	20	.038	70	.450
30	.038	80	.453	30	.051	80	.534	30	.040	80	.464
40	.039	90	.469	40	.051	90	.544	40	.040	90	.476
450	.039	800	.483	450	.052	800	.550	450	.040	800	.488
60	.040	10	.498	60	.052	10	.556	60	.041	10	.500
70	.040	20	.512	70	.051	20	.563	70	.041	20	.510
80	.040	30	.524	80	.051	30	.568	80	.042	30	.520
90	.041	40	.539	90	.052	40	.572	90	.044	40	.531
500	.043	850	.552	500	.054	850	.576	500	.047	850	.541
10	.046	60	.564	10	.056	60	.581	10	.054	60	.550
20	.054	70	.576	20	.066	70	.586	20	.070	70	.559
30	.068	80	.587	30	.081	80	.589	30	.094	80	.568
40	.082	90	.597	40	.094	90	.592	40	.110	90	.575
550	.091	900	.606	550	.100	900	.596	550	.120	900	.582
60	.096	10	.615	60	.100	10	.600	60	.124	10	.590
70	.100	20	.624	70	.094	20	.600	70	.121	20	.596
80	.102	30	.632	80	.089	30	.601	80	.118	30	.600
90	.106	40	.638	90	.086	40	.600	90	.116	40	.603
600	.112	950	.644	600	.086	950	.599	600	.118	950	.603
10	.117	60	.648	10	.085	60	.592	10	.118	60	.600
20	.122	70	.651	20	.084	70	.589	20	.118	70	.600
30	.128	80	.656	30	.084	80	.588	30	.120	80	.600
40	.133	90	.660	40	.084	90	.591	40	.119	90	.605
650	.137	1000	.664	650	.082	1000	.594	650	.114	1000	.610
60	.142	10	.669	60	.082	10	.600	60	.112	10	.618
70	.146	20	.675	70	.081	20	.605	70	.109	20	.625
80	.153	30	.679	80	.082	30	.610	80	.110	30	.632
90	.167	40	.683	90	.088	40	.614	90	.134	40	.635
700	.198	1050	.686	700	.119	1050	.618	700	.192	1050	.641
10	.237	60	.691	10	.172	60	.620	10	.252	60	.644
20	.279	70	.693	20	.250	70	.625	20	.311	70	.646
30	.325	80	.694	30	.341	80	.626	30	.359	80	.648
40	.360			40	.419			40	.396		

Diseased and Rust Resisting Wheat
(From Beltsville, Maryland)

Spectral Directional Reflectance of the Leaves of the Indicated Wheat Specimens for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix A; GE Graph Sheets Serial No. GE II-971, 972, 986, and 987.)

(7) Middle Leaves, 127-36-L Resistant (low water)

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.048	750	0.524
10	.054	60	.544
20	.060	70	.552
30	.062	80	.558
40	.064	90	.562
450	.064	800	.565
60	.065	10	.568
70	.065	20	.570
80	.065	30	.572
90	.066	40	.574
500	.070	850	.575
10	.084	60	.576
20	.112	70	.578
30	.141	80	.580
40	.155	90	.580
550	.160	900	.581
60	.158	10	.582
70	.142	20	.582
80	.124	30	.582
90	.112	40	.582
600	.106	950	.579
10	.100	60	.574
20	.091	70	.570
30	.086	80	.570
40	.080	90	.573
650	.070	1000	.576
60	.063	10	.580
70	.056	20	.585
80	.054	30	.588
90	.074	40	.591
700	.150	1050	.595
10	.250	60	.599
20	.346	70	.600
30	.434	80	.604
40	.492		

(8) Top Leaves, 127-17-L Resistant (excessive water)

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.044	750	0.532
10	.050	60	.568
20	.056	70	.586
30	.058	80	.596
40	.060	90	.602
450	.060	800	.606
60	.060	10	.609
70	.060	20	.612
80	.060	30	.614
90	.060	40	.615
500	.060	850	.616
10	.064	60	.618
20	.074	70	.620
30	.090	80	.621
40	.098	90	.622
550	.100	900	.623
60	.096	10	.624
70	.086	20	.624
80	.076	30	.624
90	.071	40	.621
600	.068	950	.616
10	.064	60	.611
20	.061	70	.606
30	.059	80	.604
40	.056	90	.606
650	.054	1000	.610
60	.051	10	.614
70	.050	20	.618
80	.050	30	.623
90	.054	40	.626
700	.086	1050	.630
10	.152	60	.631
20	.249	70	.632
30	.366	80	.634
40	.465		

(9) Leaves of Wheat Inoculated (species undesignated)

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.108	750	0.492
10	.112	60	.502
20	.117	70	.511
30	.122	80	.520
40	.126	90	.528
450	.128	800	.535
60	.132	10	.544
70	.134	20	.550
80	.136	30	.556
90	.138	40	.561
500	.142	850	.567
10	.150	60	.572
20	.168	70	.576
30	.194	80	.581
40	.218	90	.584
550	.235	900	.588
60	.246	10	.591
70	.250	20	.594
80	.248	30	.596
90	.248	40	.598
600	.250	950	.599
10	.250	60	.598
20	.248	70	.598
30	.250	80	.599
40	.249	90	.600
650	.241	1000	.602
60	.234	10	.606
70	.224	20	.608
80	.221	30	.612
90	.241	40	.614
700	.304	1050	.616
10	.370	60	.618
20	.424	70	.620
30	.458	80	.620
40	.478		

Diseased and Rust Resisting Wheat
(From Beltsville, Maryland)

Spectral Directional Reflectance of the Heads of the Indicated Wheat Specimens for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix A; GE Graph Sheets Serial No. GE II-986 and 987.)

(10) Mature Heads (Fruit)
Resisting 36 4-16-52; 5-36-L
Inoculated

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.168	750	0.658
10	.191	60	.667
20	.224	70	.674
30	.255	80	.678
40	.282	90	.682
450	.305	800	.687
60	.324	10	.691
70	.340	20	.694
80	.354	30	.697
90	.365	40	.700
500	.376	850	.702
10	.386	60	.704
20	.398	70	.706
30	.408	80	.708
40	.420	90	.708
550	.434	900	.709
60	.449	10	.707
70	.463	20	.706
80	.472	30	.706
90	.490	40	.708
600	.505	950	.708
10	.518	60	.706
20	.530	70	.702
30	.541	80	.699
40	.550	90	.694
650	.560	1000	.692
60	.570	10	.692
70	.580	20	.694
80	.590	30	.694
90	.604	40	.696
700	.616	1050	.698
10	.628	60	.698
20	.636	70	.703
30	.643	80	.704
40	.652		

(11) Mature Heads (Fruit)
LC 10/19; 38 4-23-52
Inoculated

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.149	750	0.598
10	.166	60	.608
20	.186	70	.616
30	.206	80	.623
40	.222	90	.630
450	.236	800	.636
60	.250	10	.642
70	.261	20	.648
80	.272	30	.652
90	.284	40	.657
500	.294	850	.662
10	.305	60	.666
20	.316	70	.670
30	.328	80	.672
40	.340	90	.674
550	.352	900	.676
60	.366	10	.676
70	.380	20	.678
80	.394	30	.680
90	.408	40	.682
600	.420	950	.684
10	.434	60	.683
20	.448	70	.681
30	.460	80	.678
40	.471	90	.676
650	.484	1000	.674
60	.494	10	.676
70	.507	20	.676
80	.520	30	.680
90	.533	40	.680
700	.546	1050	.682
10	.558	60	.684
20	.570	70	.686
30	.580	80	.688
40	.590		

Wheat Rust Spore
(From Beltsville, Maryland)

Spectral Directional Reflectance of Specimens of the Indicated Wheat Rust Spore for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix A; GE Graph Sheets Serial No. GE II-969, 970, 986, and 987.)

(12) Pure Spore				(13) Pure Leaf Rust				(14) Pure Stem Rust			
Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.023	750	0.284	400	0.094	750	0.377	400	0.108	750	0.366
10	.023	60	.302	10	.093	60	.392	10	.109	60	.379
20	.022	70	.319	20	.092	70	.404	20	.109	70	.390
30	.022	80	.334	30	.092	80	.418	30	.109	80	.403
40	.021	90	.350	40	.092	90	.430	40	.108	90	.415
450	.021	800	.367	450	.091	800	.444	450	.108	800	.426
60	.021	10	.383	60	.090	10	.458	60	.108	10	.440
70	.021	20	.401	70	.090	20	.474	70	.107	20	.451
80	.021	30	.417	80	.090	30	.486	80	.108	30	.464
90	.022	40	.433	90	.090	40	.500	90	.110	40	.476
500	.023	850	.449	500	.090	850	.515	500	.111	850	.490
10	.023	60	.465	10	.090	60	.531	10	.112	60	.501
20	.029	70	.480	20	.091	70	.544	20	.118	70	.514
30	.042	80	.495	30	.099	80	.558	30	.132	80	.524
40	.053	90	.508	40	.118	90	.570	40	.145	90	.535
550	.061	900	.522	550	.136	900	.584	550	.155	900	.545
60	.068	10	.536	60	.149	10	.598	60	.161	10	.556
70	.075	20	.548	70	.159	20	.611	70	.169	20	.566
80	.081	30	.561	80	.168	30	.623	80	.176	30	.576
90	.089	40	.572	90	.178	40	.634	90	.184	40	.586
600	.097	950	.584	600	.188	950	.645	600	.194	950	.594
10	.105	60	.594	10	.198	60	.654	10	.201	60	.602
20	.116	70	.604	20	.209	70	.665	20	.212	70	.610
30	.126	80	.614	30	.221	80	.675	30	.221	80	.619
40	.135	90	.624	40	.232	90	.685	40	.232	90	.626
650	.146	1000	.628	650	.244	1000	.692	650	.244	1000	.630
60	.157	10	.636	60	.256	10	.702	60	.255	10	.636
70	.169	20	.646	70	.270	20	.710	70	.266	20	.641
80	.182	30	.651	80	.284	30	.716	80	.278	30	.645
90	.194	40	.657	90	.295	40	.721	90	.290	40	.650
700	.207	1050	.658	700	.309	1050	.727	700	.304	1050	.654
10	.222	60	.663	10	.323	60	.731	10	.316	60	.656
20	.238	70	.664	20	.336	70	.735	20	.330	70	.660
30	.253	80	.668	30	.352	80	.741	30	.342	80	.664
40	.269			40	.364			40	.355		

Wheat Rust Spore
(From Beltsville, Maryland)

Spectral Transmittance of Specimens of the Indicated Wheat Rust Spore for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix A; GE Graph Sheets Serial No. GE II - 973, 974, 986, and 987.)

(15) Pure Spore 15B 5/13/52				(16) Pure Leaf Rust				(17) Pure Stem Rust			
Wave Length mμ	T_λ	Wave Length mμ	T_λ	Wave Length mμ	T_λ	Wave Length mμ	T_λ	Wave Length mμ	T_λ	Wave Length mμ	T_λ
400	0.003	750	0.014	400	0.012	750	0.134	400	0.005	750	0.032
10	.003	60	.015	10	.011	60	.144	10	.005	60	.034
20	.003	70	.016	20	.010	70	.146	20	.005	70	.036
30	.003	80	.018	30	.009	80	.148	30	.005	80	.038
40	.003	90	.020	40	.008	90	.150	40	.004	90	.040
450	.003	800	.021	450	.008	800	.151	450	.004	800	.041
60	.003	10	.023	60	.008	10	.153	60	.004	10	.044
70	.003	20	.025	70	.008	20	.155	70	.004	20	.046
80	.002	30	.027	80	.008	30	.156	80	.004	30	.048
90	.002	40	.029	90	.008	40	.158	90	.004	40	.050
500	.002	850	.031	500	.008	850	.160	500	.005	850	.051
10	.002	60	.033	10	.008	60	.161	10	.005	60	.053
20	.002	70	.035	20	.010	70	.162	20	.005	70	.055
30	.002	80	.037	30	.020	80	.164	30	.006	80	.056
40	.002	90	.039	40	.039	90	.164	40	.007	90	.058
550	.003	900	.041	550	.056	900	.166	550	.008	900	.060
60	.003	10	.042	60	.064	10	.166	60	.009	10	.061
70	.003	20	.044	70	.070	20	.167	70	.009	20	.062
80	.003	30	.046	80	.074	30	.168	80	.010	30	.064
90	.003	40	.047	90	.078	40	.168	90	.011	40	.065
600	.003	950	.049	600	.082	950	.169	600	.011	950	.066
10	.003	60	.050	10	.086	60	.170	10	.012	60	.066
20	.003	70	.052	20	.090	70	.170	20	.013	70	.068
30	.004	80	.053	30	.094	80	.170	30	.014	80	.068
40	.004	90	.054	40	.096	90	.170	40	.015	90	.069
650	.004	1000	.055	650	.100	1000	.170	650	.016	1000	.070
60	.005	10	.055	60	.104	10	.171	60	.018	10	.070
70	.006	20	.057	70	.106	20	.171	70	.019	20	.071
80	.006	30	.058	80	.110	30	.171	80	.020	30	.071
90	.007	40	.058	90	.112	40	.172	90	.022	40	.071
700	.008	1050	.059	700	.116	1050	.170	700	.024	1050	.071
10	.009	60	.060	10	.119	60	.170	10	.026	60	.071
20	.010	70	.062	20	.121	70	.170	20	.028	70	.071
30	.011	80	.064	30	.130	80	.171	30	.029	80	.071
40	.012			40	.132			40	.030		

Diseased and Rust Resisting Rye
(From Beltsville, Maryland)

Spectral Directional Reflectance of the Leaves of the Indicated Rye Specimens for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix A; GE Graph Sheets Serial No. GE II - 1376 and 1377.)

(18) Leaves of Rye Diseased				(19) Leaves of Rye Non-diseased				(20) Leaves of Rye (unpotted plant)			
Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.140	750	0.556	400	0.141	750	0.596	400	0.116	750	0.688
10	.140	60	.565	10	.144	60	.608	10	.118	60	.721
20	.140	70	.571	20	.145	70	.614	20	.118	70	.736
30	.140	80	.575	30	.144	80	.616	30	.117	80	.743
40	.140	90	.580	40	.144	90	.619	40	.116	90	.746
450	.141	800	.584	450	.144	800	.620	450	.116	800	.748
60	.142	10	.587	60	.144	10	.620	60	.116	10	.749
70	.144	20	.590	70	.144	20	.620	70	.116	20	.750
80	.144	30	.594	80	.144	30	.620	80	.116	30	.750
90	.146	40	.596	90	.144	40	.620	90	.115	40	.749
500	.154	850	.600	500	.146	850	.620	500	.119	850	.749
10	.172	60	.602	10	.159	60	.620	10	.130	60	.749
20	.202	70	.604	20	.186	70	.620	20	.155	70	.749
30	.236	80	.608	30	.214	80	.620	30	.184	80	.749
40	.256	90	.610	40	.226	90	.620	40	.195	90	.748
550	.266	900	.612	550	.230	900	.620	550	.198	900	.748
60	.269	10	.614	60	.224	10	.620	60	.193	10	.746
70	.259	20	.616	70	.206	20	.620	70	.176	20	.744
80	.246	30	.616	80	.188	30	.620	80	.159	30	.739
90	.239	40	.616	90	.178	40	.618	90	.150	40	.729
600	.235	950	.614	600	.174	950	.614	600	.144	950	.716
10	.230	60	.612	10	.166	60	.612	10	.138	60	.703
20	.223	70	.612	20	.160	70	.612	20	.131	70	.698
30	.221	80	.614	30	.156	80	.614	30	.128	80	.698
40	.214	90	.618	40	.150	90	.618	40	.123	90	.702
650	.200	1000	.621	650	.142	1000	.620	650	.116	1000	.709
60	.191	10	.626	60	.136	10	.624	60	.110	10	.716
70	.180	20	.630	70	.132	20	.628	70	.106	20	.724
80	.179	30	.634	80	.131	30	.631	80	.105	30	.730
90	.219	40	.638	90	.150	40	.634	90	.121	40	.735
700	.314	1050	.641	700	.219	1050	.638	700	.192	1050	.739
10	.398	60	.642	10	.311	60	.640	10	.288	60	.741
20	.464	70	.645	20	.410	70	.642	20	.400	70	.742
30	.516	80	.646	30	.506	80	.642	30	.530	80	.742
40	.541			40	.564			40	.626		

X. Field-Grown Specimens from Stillwater, Oklahoma

All of the 16 specimens from field-grown wheat plants grown at the USDA Plant Industry Station, Stillwater, Oklahoma, are considered in this part of this report. These specimens were from fields photographed from a plane a day or two previous to the date received at the NBS. The specimens were flown from Stillwater, Oklahoma, to Washington, D. C., and were brought to the NBS for measurement by Dr. R. N. Colwell on May 29, 1952. The specimen designations given by Dr. Colwell, together with the specimen numbers used throughout this section of this report are listed in Table V.

Figures 18 through 25 show the spectral-directional-reflectance curves of the specimens designated in the legends of the illustrations. The data used for these illustrations are taken from those shown in Appendix C and listed in Appendix D.

The chromaticity coordinates, dominant wavelength, and excitation purity of the specimens of these eight illustrations are shown in segments of the C.I.E. chromaticity diagram, for Source C, in Figures 26 through 28. The data used for these illustrations are listed in Table VI. Table VI also lists the daylight reflectance of the 16 specimens.

The Munsell renotations of these same specimens are illustrated in the schematic diagrams of the "Ideal Munsell System" in Figures 29 through 31. The data used for these illustrations are listed in Table VII together with the corresponding ISCC-NBS color designations.

Determinations were made of color difference between the related specimens indicated in Table VIII.

Figure 18. Visible and near infrared spectral directional reflectance of the leaves of two specimens of mature, field-grown, wheat plants:

(21) Leaves of WESTAR, Section 2, Field C, High rust severity

(24) Leaves of WESTAR, Section 2, Field C, Low rust severity

Figure 19. Visible and near infrared spectral directional reflectance of the heads (fruit) of two specimens of mature, field-grown, wheat plants:

(22) Heads of WESTER, Section 2, Field C, High rust severity

(25) Heads of WESTAR, Section 2, Field C, Low rust severity

Figure 20. Visible and near infrared spectral directional reflectance of the stalks of two specimens of mature, field-grown, wheat plants:

(23) Stalks of WESTAR, Section 2, Field C, High rust severity

(26) Stalks of WESTAR, Section 2, Field C, Low rust severity

Figure 21. Visible and near infrared spectral directional reflectance of the heads (fruit) of two specimens of mature, field-grown, wheat plants:

(27) Heads of WICHITA, Section 5, Field D, High rust severity

(29) Heads of WICHITA, Section 5, Field D, Low rust severity

Figure 22. Visible and near infrared spectral directional reflectance of the stalks of two specimens of mature, field-grown, wheat plants:

(28) Stalks of WICHITA, Section 5, Field D, High rust severity

(30) Stalks of WICHITA, Section 5, Field D, Low rust severity

Figure 23. Visible and near infrared spectral directional reflectance of the leaves of two specimens of mature, field-grown, wheat plants:

(31) Leaves of BLUE JACKET, Section 9, Field D

(34) Leaves of BLUE JACKET, Section 11, Field D

Figure 24. Visible and near infrared spectral directional reflectance of the heads (fruit) of two specimens of mature, field-grown, wheat plants:

(32) Heads of BLUE JACKET, Section 9, Field D

(35) Heads of BLUE JACKET, Section 11, Field D

Figure 25. Visible and near infrared spectral directional reflectance of the stalks of two specimens of mature, field-grown, wheat plants:

(33) Stalks of BLUE JACKET, Section 9, Field D

(36) Stalks of BLUE JACKET, Section 11, Field D

Figure 26. Segment of the C.I.E. chromaticity diagram showing dominant wavelength, excitation purity, and chromaticity coordinates, for Source C, of the leaves, heads, and stalks, of two specimens of mature, field grown, wheat plants:

(21) Leaves of WESTAR, Section 2, Field C, High rust severity

(22) Heads of WESTAR, Section 2, Field C, High rust severity

(23) Stalks of WESTAR, Section 2, Field C, High rust severity

(24) Leaves of WESTAR, Section 2, Field C, Low rust severity

(25) Heads of WESTAR, Section 2, Field C, Low rust severity

(26) Stalks of WESTAR, Section 2, Field C, Low rust severity

Figure 27. Segment of the C.I.E. chromaticity diagram showing dominant wavelength, excitation purity, and chromaticity coordinates, for Source C, of the heads and stalks of two specimens of mature, field-grown, wheat plants:

(27) Heads of WICHITA, Section 5, Field D, High rust severity

(28) Stalks of WICHITA, Section 5, Field D, High rust severity

(29) Heads of WICHITA, Section 5, Field D, Low rust severity

(30) Stalks of WICHITA, Section 5, Field D, Low rust severity

Figure 28. Segment of the C.I.E. chromaticity diagram showing dominant wavelength, excitation purity, and chromaticity coordinates, for Source C, of the leaves, heads, and stalks, of two specimens of mature, field-grown, wheat plants:

(31) Leaves of BLUE JACKET, Section 9, Field D

(32) Heads of BLUE JACKET, Section 9, Field D

(33) Stalks of BLUE JACKET, Section 9, Field D

(34) Leaves of BLUE JACKET, Section 11, Field D

(35) Heads of BLUE JACKET, Section 11, Field D

(36) Stalks of BLUE JACKET, Section 11, Field D

Figure 29. Schematic illustration of the vertical and horizontal projections of the "ideal" Munsell system showing the Munsell Value (upper diagram) plotted against the Munsell Hue and Chroma points projected from the lower diagram of the leaves, heads, and stalks, of two specimens of mature, field-grown, wheat plants:

(21) Leaves of WESTAR, Section 2, Field C, High rust severity

(22) Heads of WESTAR, Section 2, Field C, High rust severity

(23) Stalks of WESTAR, Section 2, Field C, High rust severity

(24) Leaves of WESTAR, Section 2, Field C, Low rust severity

(25) Heads of WESTAR, Section 2, Field C, Low rust severity

(26) Stalks of WESTAR, Section 2, Field C, Low rust severity

Figure 30. Schematic illustration of the vertical and horizontal projections of the "ideal" Munsell system showing the Munsell Value (upper diagram) plotted against the Munsell Hue and Chroma points projected from the lower diagram of the heads and stalks of two specimens of mature, field-grown, wheat plants:

(27) Heads of WICHITA, Section 5, Field D, High rust severity

(28) Stalks of WICHITA, Section 5, Field D, High rust severity

(29) Heads of WICHITA, Section 5, Field D, Low rust severity

(30) Stalks of WICHITA, Section 5, Field D, Low rust severity

Figure 31. Schematic illustration of the vertical and horizontal projections of the "ideal" Munsell system showing the Munsell Value (upper diagram) plotted against the Munsell Hue and Chroma points projected from the lower diagram of the leaves, heads, and stalks, of two specimens of mature, field-grown, wheat plants:

(31) Leaves of BLUE JACKET, Section 9, Field D

(32) Heads of BLUE JACKET, Section 9, Field D

(33) Stalks of BLUE JACKET, Section 9, Field D

(34) Leaves of BLUE JACKET, Section 11, Field D

(35) Heads of BLUE JACKET, Section 11, Field D

(36) Stalks of BLUE JACKET, Section 11, Field D

Table V

List of the specimens raised at Stillwater, Oklahoma, and brought to the NBS by Dr. Colwell on May 29, 1952.

Object Number	Specimen Designations
(21)	Leaves of WESTAR, Section 2, Field C, High Rust Severity
(22)	Heads of WESTAR, Section 2, Field C, High Rust Severity
(23)	Stalks of WESTAR, Section 2, Field C, High Rust Severity
(24)	Leaves of WESTAR, Section 2, Field C, Low Rust Severity
(25)	Heads of WESTAR, Section 2, Field C, Low Rust Severity
(26)	Stalks of WESTAR, Section 2, Field C, Low Rust Severity
(27)	Heads of WICHITA, Section 5, Field D, High Rust Severity
(28)	Stalks of WICHITA, Section 5, Field D, High Rust Severity
(29)	Heads of WICHITA, Section 5, Field D, Low Rust Severity
(30)	Stalks of WICHITA, Section 5, Field D, Low Rust Severity
(31)	Leaves of BLUE JACKET, Section 9, Field D
(32)	Heads of BLUE JACKET, Section 9, Field D
(33)	Stalks of BLUE JACKET, Section 9, Field D
(34)	Leaves of BLUE JACKET, Section 11, Field D
(35)	Heads of BLUE JACKET, Section 11, Field D
(36)	Stalks of BLUE JACKET, Section 11, Field D

Table VI

Specimens from Stillwater, Oklahoma

Chromaticity Coordinates, Daylight Reflectances, Dominant Wavelength and Excitation Purity for C.I.E. Source C of the Specimens Studied.

Specimen Number	Chromaticity Coordinates x	y	Daylight Reflectance Y(%)	Dominant Wavelength (mμ)	Excitation Purity (%)
(21)	0.364	0.367	22.9	578.5	28.0
(22)	.339	.370	20.3	569.4	22.1
(23)	.329	.365	17.8	565.8	18.0
(24)	.330	.363	18.9	566.4	17.9
(25)	.342	.371	20.9	570.3	23.1
(26)	.336	.378	20.9	566.4	23.4
(27)	.357	.373	26.0	575.0	27.8
(28)	.376	.387	43.5	576.6	36.8
(29)	.343	.372	23.3	570.6	23.7
(30)	.334	.370	20.6	567.2	20.9
(31)	.340	.369	21.0	570.0	22.2
(32)	.342	.374	20.4	569.8	24.0
(33)	.330	.367	19.0	566.0	18.9
(34)	.338	.366	18.8	569.9	20.8
(35)	.342	.375	21.7	569.6	24.3
(36)	.328	.363	17.8	565.6	17.2

Table VII

Specimens from Stillwater, Oklahoma

Munsell Renotations and ISCC-NBS Color Designations of the Specimens Studied

Specimen Number	Munsell Renotation	ISCC-NBS Color Designation
(21)	2.4Y 5.3/2.3	Light olive brown
(22)	2.4GY 5.1/2.2	Grayish yellow green
(23)	5.3GY 4.8/2.1	Grayish yellow green
(24)	4.9GY 4.9/2.0	Grayish yellow green
(25)	1.5GY 5.1/2.3	Light grayish olive
(26)	4.9GY 5.1/2.6	Grayish yellow green
(27)	5.9Y 5.6/2.6	Light grayish olive
(28)	4.0Y 7.0/4.2	Grayish yellow
(29)	1.3GY 5.4/2.4	Light grayish olive
(30)	4.3GY 5.1/2.3	Grayish yellow green
(31)	1.7GY 5.1/2.2	Light grayish olive
(32)	2.0GY 5.1/2.4	Grayish yellow green
(33)	5.2GY 4.9/2.2	Grayish yellow green
(34)	1.6GY 4.9/2.0	Light grayish olive
(35)	2.3GY 5.2/2.4	Grayish yellow green
(36)	5.4GY 4.8/2.0	Grayish yellow green

Table VIII

Specimens from Stillwater, Oklahoma

Color Differences Computed from the Godlove Color-Difference Formula between the Specimens Indicated.

Color Difference Between Specimens Number Reference	Comparison	Color Difference ΔE
(24)	(21)	11.6
(25)	(22)	0.8
(26)	(23)	6.5
(21)	(22)	8.0
(21)	(23)	13.3
(24)	(25)	4.8
(24)	(26)	5.0
(27)	(29)	5.9
(28)	(30)	40.4
(31)	(34)	4.1
(32)	(35)	2.0
(33)	(36)	2.2
(31)	(32)	1.0
(31)	(33)	4.6
(34)	(35)	6.3
(34)	(36)	3.1

Appendix C

Ozalid copies of the original spectrophotometric recordings of the 16 field-grown specimens of wheat from Stillwater, Oklahoma, made on a General Electric recording spectrophotometer.

Index to Appendix C

Specimen Number	GE Graph Sheet Serial Number: Visible Spectrum	GE Graph Sheet Serial Number: Near Infrared Spectrum	Curve Number	Date Measured
(21)	GE II- 975	GE II- 976	1	5-29-52
(22)	- 980	- 977	1	5-29-52
(23)	- 979	- 978	1	5-29-52
(24)	- 975	- 976	2	5-29-52
(25)	- 980	- 977	2	5-29-52
(26)	- 979	- 978	2	5-29-52
(27)	- 981	- 982	1	5-29-52
(28)	- 981	- 982	2	5-29-52
(29)	- 981	- 982	3	5-29-52
(30)	- 981	- 982	4	5-29-52
(31)	- 984	- 983	1	5-29-52
(32)	- 984	- 983	2	5-29-52
(33)	- 984	- 983	3	5-29-52
(34)	- 984	- 983	4	5-29-52
(35)	- 984	- 983	5	5-29-52
(36)	- 984	- 983	6	5-29-52

Appendix D

Tables of spectral directional reflectance read from the spectrophotometric curves of Appendix C.

Field Infected Wheat
(From Stillwater, Oklahoma)

Spectral Directional Reflectance of the Indicated Parts of Field Infected Mature Wheat Crops for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix C; GE Graph Sheets Serial No. GE II - 975, 976, 977, 978, 979, and 980.)

(21) Leaves of Westar Section 2, Field C High Rust Severity				(22) Heads of Westar Section 2, Field C High Rust Severity				(23) Stalks of Westar Section 2, Field C High Rust Severity			
Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.110	750	0.498	400	0.100	750	0.573	400	0.100	750	0.635
10	.117	60	.509	10	.106	60	.600	10	.104	60	.663
20	.124	70	.519	20	.114	70	.614	20	.112	70	.678
30	.129	80	.528	30	.121	80	.622	30	.119	80	.685
40	.134	90	.536	40	.128	90	.626	40	.124	90	.688
450	.140	800	.545	450	.135	800	.630	450	.126	800	.690
60	.146	10	.554	60	.140	10	.632	60	.128	10	.690
70	.150	20	.562	70	.142	20	.634	70	.130	20	.691
80	.156	30	.570	80	.145	30	.634	80	.130	30	.692
90	.160	40	.578	90	.148	40	.634	90	.131	40	.692
500	.166	850	.585	500	.155	850	.634	500	.134	850	.692
10	.176	60	.591	10	.169	60	.634	10	.144	60	.692
20	.190	70	.598	20	.189	70	.633	20	.164	70	.692
30	.208	80	.603	30	.210	80	.633	30	.189	80	.692
40	.224	90	.608	40	.223	90	.632	40	.204	90	.692
550	.236	900	.614	550	.229	900	.631	550	.209	900	.692
60	.244	10	.619	60	.230	10	.629	60	.207	10	.692
70	.250	20	.623	70	.223	20	.626	70	.196	20	.692
80	.251	30	.626	80	.212	30	.622	80	.180	30	.691
90	.256	40	.630	90	.206	40	.615	90	.171	40	.688
600	.260	950	.634	600	.202	950	.602	600	.166	950	.684
10	.264	60	.636	10	.199	60	.586	10	.162	60	.677
20	.265	70	.639	20	.191	70	.572	20	.156	70	.670
30	.270	80	.642	30	.189	80	.565	30	.151	80	.668
40	.270	90	.645	40	.184	90	.563	40	.148	90	.668
650	.265	1000	.648	650	.175	1000	.566	650	.140	1000	.670
60	.262	10	.652	60	.166	10	.570	60	.135	10	.674
70	.260	20	.654	70	.154	20	.578	70	.128	20	.678
80	.266	30	.658	80	.150	30	.586	80	.126	30	.681
90	.294	40	.659	90	.170	40	.591	90	.136	40	.686
700	.350	1050	.661	700	.230	1050	.598	700	.190	1050	.690
10	.399	60	.664	10	.300	60	.601	10	.279	60	.692
20	.438	70	.666	20	.380	70	.606	20	.385	70	.695
30	.465	80	.669	30	.458	80	.608	30	.492	80	.697
40	.484			40	.528			40	.579		

Field Infected Wheat
(From Stillwater, Oklahoma)

Spectral Directional Reflectance of the Indicated Parts of Field Infected Mature Wheat Crops for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix C; GE Graph Sheets Serial No. GE II -975, 976, 977, 978, 979, and 980.)

(24) Leaves of Westar
Section 2, Field C
Low Rust Severity

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.114	750	0.598
10	.116	60	.624
20	.122	70	.639
30	.129	80	.646
40	.134	90	.650
450	.136	800	.653
60	.138	10	.656
70	.138	20	.658
80	.139	30	.660
90	.140	40	.661
500	.145	850	.664
10	.156	60	.665
20	.176	70	.666
30	.200	80	.668
40	.214	90	.669
550	.220	900	.670
60	.218	10	.670
70	.206	20	.671
80	.192	30	.672
90	.184	40	.671
600	.180	950	.670
10	.176	60	.666
20	.169	70	.664
30	.166	80	.664
40	.161	90	.665
650	.153	1000	.666
60	.146	10	.670
70	.140	20	.673
80	.138	30	.675
90	.154	40	.678
700	.216	1050	.681
10	.295	60	.682
20	.384	70	.682
30	.480	80	.684
40	.552		

(25) Heads of Westar
Section 2, Field C
Low Rust Severity

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.100	750	0.575
10	.106	60	.600
20	.114	70	.614
30	.122	80	.622
40	.130	90	.626
450	.136	800	.630
60	.142	10	.632
70	.146	20	.634
80	.148	30	.634
90	.151	40	.634
500	.158	850	.634
10	.172	60	.634
20	.192	70	.633
30	.214	80	.633
40	.226	90	.632
550	.234	900	.631
60	.236	10	.629
70	.230	20	.626
80	.220	30	.620
90	.214	40	.612
600	.210	950	.600
10	.206	60	.582
20	.200	70	.566
30	.198	80	.558
40	.194	90	.558
650	.184	1000	.560
60	.176	10	.566
70	.164	20	.574
80	.160	30	.582
90	.180	40	.591
700	.240	1050	.598
10	.316	60	.601
20	.396	70	.606
30	.470	80	.608
40	.532		

(26) Stalks of Westar
Section 2, Field C
Low Rust Severity

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.104	750	0.670
10	.108	60	.695
20	.116	70	.708
30	.124	80	.714
40	.130	90	.716
450	.134	800	.718
60	.136	10	.719
70	.138	20	.720
80	.139	30	.720
90	.141	40	.720
500	.146	850	.720
10	.162	60	.720
20	.191	70	.720
30	.225	80	.720
40	.244	90	.720
550	.250	900	.720
60	.250	10	.720
70	.234	20	.719
80	.214	30	.717
90	.201	40	.714
600	.195	950	.708
10	.189	60	.700
20	.179	70	.691
30	.174	80	.688
40	.168	90	.688
650	.156	1000	.690
60	.148	10	.694
70	.136	20	.700
80	.132	30	.704
90	.150	40	.710
700	.224	1050	.714
10	.330	60	.716
20	.441	70	.719
30	.540	80	.720
40	.622		

Field Infected Wheat
(From Stillwater, Oklahoma)

Spectral Directional Reflectance of the Indicated Parts of Field Infected Mature Wheat Crops for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix C; GE Graph Sheets Serial No. GE II - 981 and 982.)

(27) Heads of Wichita
Section 5, Field D
High Rust Severity

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.104	750	0.512
10	.112	60	.514
20	.126	70	.519
30	.138	80	.524
40	.149	90	.528
450	.157	800	.534
60	.164	10	.536
70	.171	20	.540
80	.175	30	.542
90	.180	40	.544
500	.189	850	.546
10	.205	60	.548
20	.227	70	.550
30	.250	80	.552
40	.265	90	.553
550	.276	900	.553
60	.284	10	.552
70	.286	20	.552
80	.284	30	.550
90	.283	40	.548
600	.284	950	.541
10	.283	60	.531
20	.280	70	.520
30	.278	80	.514
40	.276	90	.512
650	.264	1000	.514
60	.255	10	.518
70	.239	20	.524
80	.234	30	.530
90	.264	40	.536
700	.338	1050	.542
10	.404	60	.546
20	.453	70	.550
30	.479	80	.554
40	.500		

(28) Stalks of Wichita
Section 5, Field D
High Rust Severity

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.108	750	0.719
10	.122	60	.726
20	.154	70	.728
30	.188	80	.730
40	.212	90	.732
450	.228	800	.732
60	.238	10	.734
70	.248	20	.734
80	.252	30	.734
90	.257	40	.735
500	.270	850	.736
10	.298	60	.736
20	.344	70	.736
30	.399	80	.736
40	.441	90	.736
550	.469	900	.736
60	.488	10	.736
70	.496	20	.736
80	.496	30	.735
90	.496	40	.734
600	.500	950	.732
10	.499	60	.729
20	.494	70	.726
30	.492	80	.724
40	.488	90	.724
650	.469	1000	.724
60	.450	10	.726
70	.420	20	.728
80	.410	30	.732
90	.461	40	.735
700	.562	1050	.736
10	.634	60	.736
20	.674	70	.739
30	.700	80	.740
40	.712		

Field Infected Wheat
(From Stillwater, Oklahoma)

Spectral Directional Reflectance of the Indicated Parts of Field Infected Mature Wheat Crops for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix C; GE Graph Sheets Serial No. GE II - 981 and 982.)

(29) Heads of Wichita Section 5, Field D Low Rust Severity				(30) Stalks of Wichita Section 5, Field D Low Rust Severity			
Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.114	750	0.574	400	0.104	750	0.664
10	.120	60	.593	10	.112	60	.691
20	.130	70	.604	20	.121	70	.706
30	.138	80	.610	30	.130	80	.712
40	.144	90	.616	40	.136	90	.715
450	.150	800	.619	450	.140	800	.716
60	.155	10	.622	60	.143	10	.718
70	.158	20	.624	70	.144	20	.719
80	.160	30	.626	80	.144	30	.720
90	.163	40	.625	90	.146	40	.720
500	.172	850	.625	500	.150	850	.720
10	.188	60	.626	10	.163	60	.720
20	.213	70	.627	20	.186	70	.720
30	.238	80	.628	30	.218	80	.720
40	.254	90	.626	40	.236	90	.720
550	.262	900	.625	550	.244	900	.719
60	.264	10	.623	60	.244	10	.718
70	.258	20	.620	70	.231	20	.718
80	.248	30	.616	80	.214	30	.716
90	.239	40	.608	90	.201	40	.711
600	.236	950	.596	600	.196	950	.705
10	.231	60	.578	10	.190	60	.696
20	.224	70	.562	20	.182	70	.686
30	.220	80	.554	30	.178	80	.680
40	.214	90	.551	40	.172	90	.675
650	.202	1000	.554	650	.161	1000	.676
60	.192	10	.560	60	.154	10	.687
70	.178	20	.566	70	.145	20	.692
80	.172	30	.576	80	.141	30	.699
90	.194	40	.583	90	.154	40	.703
700	.264	1050	.588	700	.220	1050	.708
10	.339	60	.595	10	.318	60	.711
20	.414	70	.600	20	.425	70	.712
30	.484	80	.602	30	.530	80	.714
40	.539			40	.613		

Field Infected Wheat
(From Stillwater, Oklahoma)

Spectral Directional Reflectance of the Indicated Parts of Field Infected Mature Wheat Crops for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix C; GE Graph Sheets Serial No. GE II - 983 and 984.)

(31) Leaves of Blue Jacket Section 9, Field D				(32) Heads of Blue Jacket Section 9, Field D				(33) Stalks of Blue Jacket Section 9, Field D			
Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.106	750	0.593	400	0.098	750	0.541	400	0.098	750	0.653
10	.114	60	.630	10	.103	60	.563	10	.104	60	.676
20	.122	70	.644	20	.110	70	.575	20	.114	70	.691
30	.130	80	.653	30	.118	80	.582	30	.122	80	.698
40	.136	90	.660	40	.125	90	.587	40	.129	90	.701
450	.140	800	.666	450	.130	800	.591	450	.134	800	.702
60	.144	10	.670	60	.136	10	.596	60	.136	10	.704
70	.146	20	.676	70	.138	20	.598	70	.138	20	.706
80	.148	30	.680	80	.140	30	.600	80	.139	30	.706
90	.150	40	.684	90	.144	40	.602	90	.141	40	.706
500	.155	850	.688	500	.150	850	.604	500	.146	850	.708
10	.169	60	.692	10	.168	60	.606	10	.158	60	.708
20	.192	70	.695	20	.189	70	.606	20	.180	70	.709
30	.216	80	.698	30	.211	80	.609	30	.204	80	.710
40	.232	90	.700	40	.224	90	.609	40	.216	90	.710
550	.240	900	.702	550	.230	900	.608	550	.221	900	.710
60	.240	10	.705	60	.230	10	.606	60	.219	10	.710
70	.232	20	.706	70	.224	20	.605	70	.206	20	.710
80	.220	30	.708	80	.214	30	.602	80	.192	30	.710
90	.213	40	.710	90	.208	40	.596	90	.184	40	.709
600	.210	950	.710	600	.206	950	.584	600	.180	950	.706
10	.205	60	.707	10	.200	60	.569	10	.175	60	.701
20	.199	70	.705	20	.194	70	.555	20	.168	70	.696
30	.196	80	.704	30	.190	80	.548	30	.164	80	.694
40	.192	90	.706	40	.186	90	.546	40	.160	90	.694
650	.180	1000	.708	650	.176	1000	.550	650	.152	1000	.695
60	.172	10	.711	60	.166	10	.556	60	.146	10	.698
70	.162	20	.714	70	.152	20	.564	70	.138	20	.700
80	.161	30	.718	80	.150	30	.572	80	.135	30	.704
90	.183	40	.720	90	.174	40	.580	90	.150	40	.708
700	.254	1050	.723	700	.238	1050	.586	700	.210	1050	.708
10	.334	60	.724	10	.309	60	.592	10	.300	60	.710
20	.411	70	.723	20	.384	70	.594	20	.413	70	.714
30	.497	80	.725	30	.454	80	.596	30	.511	80	.715
40	.556			40	.507			40	.598		

Field Infected Wheat
(From Stillwater, Oklahoma)

Spectral Directional Reflectance of the Indicated Parts of Field Infected Mature Wheat Crops for the Visible and Near Infrared Spectrum, 400 to 1080 Millimicrons. (See Appendix C; GE Graph Sheets Serial No. GE II - 983 and 984.)

(34) Leaves of Blue Jacket Section 11, Field D

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.106	750	0.572
10	.111	60	.607
20	.116	70	.625
30	.124	80	.635
40	.125	90	.643
450	.128	800	.650
60	.131	10	.658
70	.132	20	.664
80	.132	30	.670
90	.134	40	.675
500	.139	850	.680
10	.150	60	.685
20	.170	70	.690
30	.194	80	.694
40	.208	90	.698
550	.216	900	.700
60	.216	10	.704
70	.208	20	.706
80	.198	30	.709
90	.190	40	.708
600	.186	950	.706
10	.182	60	.701
20	.176	70	.698
30	.174	80	.696
40	.169	90	.698
650	.158	1000	.700
60	.151	10	.706
70	.143	20	.710
80	.142	30	.715
90	.162	40	.720
700	.229	1050	.722
10	.310	60	.726
20	.394	70	.726
30	.473	80	.728
40	.533		

(35) Heads of Blue Jacket Section 11, Field D

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.106	750	0.582
10	.111	60	.600
20	.116	70	.616
30	.124	80	.624
40	.130	90	.630
450	.138	800	.634
60	.144	10	.638
70	.146	20	.640
80	.148	30	.642
90	.151	40	.642
500	.161	850	.643
10	.178	60	.644
20	.202	70	.646
30	.226	80	.646
40	.240	90	.646
550	.246	900	.645
60	.246	10	.644
70	.239	20	.642
80	.227	30	.638
90	.220	40	.629
600	.216	950	.615
10	.211	60	.596
20	.204	70	.578
30	.200	80	.570
40	.196	90	.570
650	.184	1000	.572
60	.174	10	.580
70	.160	20	.589
80	.155	30	.596
90	.182	40	.608
700	.254	1050	.614
10	.334	60	.620
20	.412	70	.627
30	.484	80	.629
40	.542		

(36) Stalks of Blue Jacket Section 11, Field D

Wave Length mμ	R_λ	Wave Length mμ	R_λ
400	0.098	750	0.622
10	.103	60	.650
20	.110	70	.664
30	.118	80	.671
40	.125	90	.674
450	.128	800	.676
60	.131	10	.678
70	.132	20	.679
80	.132	30	.680
90	.134	40	.680
500	.139	850	.681
10	.150	60	.682
20	.169	70	.682
30	.190	80	.683
40	.202	90	.684
550	.206	900	.684
60	.204	10	.684
70	.193	20	.684
80	.180	30	.683
90	.171	40	.681
600	.168	950	.678
10	.164	60	.672
20	.156	70	.666
30	.154	80	.664
40	.150	90	.664
650	.143	1000	.666
60	.138	10	.670
70	.130	20	.674
80	.128	30	.678
90	.141	40	.680
700	.194	1050	.682
10	.278	60	.684
20	.382	70	.685
30	.484	80	.686
40	.570		

XI. Discussion

The spectrophotometry of diseased and healthy cereal crops shows that the spectral directional reflectance of the diseased wheat and rye plants differ from that of healthy wheat and rye plants in two regions of the 400 to 1080 millimicron spectrum studied; namely, 600 to 700 millimicrons in the visible spectrum, and 750 to 900 millimicrons in the near infrared spectrum. The average spectral directional reflectances of the diseased wheat specimens behind a cover glass were found to be 0.228 at 650 millimicrons and 0.565 at 800 millimicrons. Those for the healthy specimens were found to be 0.145 and 0.655, respectively. After subtracting 0.080 from each of these values to correct for light reflected from the cover glass, we find the reflectance ratio, diseased to healthy, to be 2.2_5 at 650 millimicrons and 0.8_5 at 800 millimicrons.

These differences are more prominent for the leaves of the young wheat plants, the leaves of the young rye plants, the leaves of Westar, and the heads of Wichita (Figures 1, 2, 3, 15, 18, and 21) than for the stalks of Westar and Wichita, and the leaves, heads and stalks of Blue Jacket. These latter do not show the crossing over of the curves of high and low severity of infestation at wavelength 730 millimicrons (Figures 20, 22, 23, 24, and 25).

Both of the young wheat plants of the susceptible variety kept at low and at excessive water content showed signs of disease (Figure 2), with the plant kept at low water content showing the more advanced degree. No evidence of disease was indicated in either of the young wheat plants of the resisting variety (Figure 3), one kept at low, the other at excessive water. These plants behaved as any other plant would when allowed to dry [1]. Similarly, the unpotted rye plant with soil around its roots and wrapped in wet paper showed the same characteristics as the wheat plant kept at excessive water content and with no signs of disease (Figure 15).

The detection of diseased wheat heads in the early stages of maturity is quite similar to detection of diseased leaves as may be seen by comparing Figure 21 for the heads of Wichita for high and for low rust severity with Figures 1, 2, 3, 15, and 18. Note that the chlorophyll absorption band at 670 millimicrons is weaker for the plants having high rust severity, regardless of whether the leaves or the heads are considered. Similarly, both leaves and heads of the plants having high rust severity show a decreased reflectance in the infrared (750 to 900 millimicrons) region of the spectrum which like the weakening of the chlorophyll band corresponds to highly increased numbers of spores on the plant (see Figure 9 for the spectral directional reflectance of spores alone). On the other hand, this pattern of reflectance changes fails to appear in the measurements (Figure 4) of the cultured plants from Beltsville, Maryland. From the absence of the chlorophyll bands in Figure 4 and from the much lessened absorption bands for water at 980 millimicrons, it is apparent that the heads of these cultured plants are over-ripe and dried out compared to the specimens of heads of Wichita whose reflectances are shown in Figure 21. Nevertheless, the inoculated heads of the over-ripe susceptible plants show decreased reflect-

ance throughout the spectrum compared to rust-resisting plants quite consistent with the presence of increased numbers of spores on the plant structure. Although the spectral directional reflectance of the spores alone is superficially similar to that of the rust-resisting over-ripe wheat heads in that there is a regular increase in reflectance with wavelength, this increase starts at a longer wavelength (520 millimicrons) for the spores than it does for the over-ripe wheat heads (less than 400 millimicrons) and corresponds to the more reddish color of the spores (compare in Table III light grayish reddish brown with light grayish yellowish brown).

The spectral directional reflectance curve of rust spore (Figure 9) shows the extreme position of change that a leaf, stem or head may reach if fully covered with spore. While possibly not significant, the spectral-transmittance curve of the leaf rust spore (Figure 10) shows greater structure than the stem rust spore or of the pure spore specimens. Leaf rust spore absorbs strongly in the 400 to 520 millimicron region of the spectrum and transmits somewhat between 530 and 1080 millimicrons while the other two spore specimens absorb more strongly throughout the visible spectrum and transmit only slightly in the near infrared spectrum. This could be explained by the fact that the leaf rust spores have finer grains than the stem rust spores and a uniform thin sample of leaf rust could be obtained. Stem rust spores did not spread well enough to obtain a sufficiently uniform thin specimen.

All of the C.I.E. chromaticity diagrams show the leaves of the diseased plants to be redder than the leaves of the healthy plants (Figures 5, 6, 16, and 26). The chromaticity points for the leaves of the healthy plants plotted between dominant wavelengths 557 and 567 millimicrons; the diseased plants, between 571 and 584 millimicrons; and the spore specimens, between 587 and 591 millimicrons. The excitation purities and daylight reflectances of the leaves of the diseased and healthy plants were essentially the same.

The charts showing these data in terms of the Munsell renotations (Figures 7, 8, 17, and 29) likewise indicate this clear-cut division of the leaf colors. The leaves of the healthy specimens are shown to have Munsell hues between 9GY and 4GY; the diseased plants, between 1GY and 9YR; and the spore specimens, between 7YR and 2YR. The ISCC-NBS color designations center about grayish yellow green for the leaves of the healthy plants; grayish olive, for the leaves of the diseased plants; and moderate brown, for the spore specimens. The designation of this disease as <u>rust</u> is thus seen to be quite apt.

The color differences computed between the various pairs of diseased and healthy specimens show that the leaves of healthy wheat or rye plants vary among individual species by less than one NBS unit of color difference while differences between the leaves and stalks of diseased and healthy plants vary between 8 and 40 or more NBS units of color difference depending upon the degree of severity of rust infestation. Large color differences such as these should be readily detectable by ordinary color photography.

Differences between the heads and the stalks of diseased and healthy plants vary erratically. The heads of Westar, Blue Jacket, and Wichita show differences between specimens of high and of low rust severity of 0.8, 2.0, and 6.5 NBS units of color difference respectively, while the heads of the susceptible and resisting controlled plants showed color differences of 12.1 NBS units of color difference. Similarly, the stalks of Blue Jacket, Westar, and Wichita for high and low rust severity showed differences of 2.2, 6.5, and 40.4 NBS units of color difference. In contrast to these differences, those obtained for the leaves of the diseased and of the healthy plants varied much more consistently; that is, Blue Jacket, 4.1, Westar, 11.6, Rye 11.3, and Suwan, 7.9 NBS units of color difference.

In order to photograph with maximum brightness contrast these differences between diseased and healthy plants within the visible spectrum on black-and-white film, it is necessary to eliminate all of the spectrum except that portion exhibiting the greatest difference (600 to 700 millimicrons). This may be accomplished by using panchromatic film combined with an orange-red filter. The panchromatic film serves a dual role, first, as receiver for the desired spectral range (600 to 700 millimicrons), and second, as eliminator of undesired energy in the far-red and infra-red parts of the spectrum (wavelengths greater than 700 millimicrons) in which the film is insensitive. The orange-red glass or gelatin filter serves to absorb the undesired radiant energy of wavelengths less than 600 millimicrons. Suggested glass filters, available for this purpose from Corning Glass Works, Corning, N. Y., are Color Spec. Nos. 2-61 and 2-62 (Glass Code 2412 and 2418, respectively) in standard thicknesses of about 3.0 mm. Alternatively, Wratten filter 29, or possibly 24, 25a, or 26, available from Eastman Kodak Company, Rochester, N. Y., may be used.

In order to photograph with maximum brightness contrast these differences between diseased and healthy plants within the infrared spectrum, it is necessary to eliminate all of the spectrum except that portion exhibiting the second greatest difference (750 to 900 millimicrons). This may be accomplished by using so-called infrared photographic film combined with a deep red filter. The infrared film serves a dual role, first, as receiver for the desired spectral range (750 to 900 millimicrons), and, second, as eliminator of the radiant energy of wavelength greater than 900 millimicrons to which the film is relatively insensitive. The deep red filter of glass or gelatin serves to absorb the undesired radiant energy of wavelength less than 750 millimicrons. Suggested filters are Wratten filter 87 or Corning glass code 2540, Color Spec. No. 7-56, in standard thickness of approximately 3.0 mm.

The healthy plants will appear dark on the photographic print from the film taken in the 600 to 700 millimicron region of the spectrum and the diseased plants will appear lighter. The lightness contrast will depend upon the degree of infestation. On the photographic film taken in the 750 to 900 millimicron region of the spectrum, the healthy plants will appear light and the diseased plants darker. In this case, the greater the degree of infestation, the darker will be the rendition.

Information on the spectrophotometric behavior of the controlled plants from Beltsville, Maryland, was orally given to Lt. Comdr. R. N. Colwell prior to the U. S. Navy flight (May 1952) over the wheat fields of Stillwater, Oklahoma, together with proposed methods for the isolation of the two regions of the spectrum discussed above. After the Stillwater flight, spectrophotometric data on the leaves of Westar wheat from Stillwater were obtained (May 29, 1952) and were given to Comdr. Colwell on the same day. These methods and data were presented by him at various meetings in 1952 (see Chronology, Appendix E), and by Keegan [12] before the 19th Meeting of the American Society of Photogrammetry in January 1953.

The results of examining the photographs taken on these Stillwater flights are summarized in a report [13] of the U. S. Naval Photointerpretation Center, signed by L. W. Keith, officer-in-charge, as follows (page 3): "The tonal comparison on the panchromatic film with both the 12 and 25A filters shows some promise. However, in this test area the infrared film was not of much value." This result, though disappointing for the infrared film, was not entirely unanticipated; note that the average contrast at 800 millimicrons is only 15% compared to 125% at 650 millimicrons (Suwon, Figure 1; Westar, Figure 18).

A second test of the recommended film-filter combinations was made on August 14, 1952. Aerial photographs were made of 7 plots (5 rows of plants per plot) of wheat growing at the Plant Industry Station, USDA, Langdon, North Dakota. The infestation of each plot with the pathogen, Puccinia graminis tritici, which causes black stem rust of wheat, was recorded, and the record indicates infestations varying from 5% to 80%. The results of examining the photographs taken on these Langdon flights was summarized in the Keith report [13] as follows (page 4): "The plots of high rust incidence showed up very clearly on infrared and color photography. The prints from panchromatic film with minus blue filter showed various tones of gray but the differences were not confined to either diseased or healthy wheat. The same applied to the coverage using panchromatic film with 25A filter."

Two comments may be made on this summary. In the first place the photographs accompanying the report [13] seem to show that both of the recommended film-filter combinations are successful, and indeed the distinctions on the photograph taken by means of panchromatic film with filter 25A are clearer than those taken on infrared film with filter 89A. In other words we see the results of this test as confirming our choices of film-filter combinations based on wheat plants (Westar) of a probably different variety infested with a different pathogen, Puccinia triticina, which causes leaf rust of wheat rather than black stem rust, and this apparent confirmation suggests that the spectral characteristics of the wheat plants growing in Langdon are closely those of the Stillwater plants. On the other hand, if the summary (which may be based on better prints) is really correct, then failure of our first-choice filter-film combination may simply be an indication that the Langdon plants differ in spectral character importantly from the Stillwater plants.

It may be noted in passing that the graph of the spectral data included in the Keith report, subsequently copied in a paper by Truesdell [14], although intended to be identical with Figure 18 of the present report, actually contained serious errors of transcription as noted in Truesdell's second paper [14].

These two attempts to utilize film-filter combinations indicated by spectrophotometric studies of wheat plants, though obviously not conclusive, nevertheless indicate that the method of detecting rust-infected wheat fields by aerial photography has considerable promise. Extensive additional field tests should be made by color photography and by black-and-white photography with film-filter combinations precisely in accord with those indicated by spectrophotometry for the particular plants and pathogens involved. Colwell [15, 16] has undertaken some of these needed field tests and presented a number of his new photographs at the National Bureau of Standards on August 19, 1954.

XII. Conclusions

1. All specimens studied, both wheat and rye, indicate that plants infected with wheat rust are redder than non-infected plants of the same kind.

2. The diseased and non-diseased rye specimens showed the same kinds of differences as diseased and non-diseased wheat specimens.

3. The spectral regions within which the ratio of spectral reflectance of the diseased specimens to that for the healthy specimens was greatest is 600 to 700 millimicrons, and that within which it is next greatest is 750 to 900 millimicrons.

4. For the most certain detection of wheat rust by black-and-white aerial photography, a combination of filters and photographic film maximally sensitive within the spectral range (600 to 700 millimicrons) is indicated.

XIII. Bibliography

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[16] R. N. Colwell, Determining the prevalence of certain cereal crop diseases by means of aerial photography (in press) 1956.

Appendix E

Chronology of pertinent events in these investigations from the first meeting in which NBS personnel participated in April 1952 to the preparation of the present report in July 1956.

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April 2, 1952. Meeting to initiate this study called by Dr. Everett F. Davis, Executive Secretary, Committee on Plant and Crop Ecology, National Research Council. Meeting held in the laboratory of Dr. Robert B. Withrow, Director, Division of Radiation of Organisms, Smithsonian Institution, Washington, D. C. Those present were: Dr. E. F. Davis, Dr. R. B. Withrow, Mrs. R. B. Withrow, Miss B. B. Britton, Dr. H. T. O'Neill, Lt. Cmdr. R. N. Colwell, Mr. R. C. Heller, Mr. R. H. Moyer, Dr. W. S. Benninghoff, and Mr. H. J. Keegan.

May 1, 1952. The second planning meeting was held in Dr. Davis' offices in the Dupont Circle Building, Washington, D. C. Those present were: Dr. E. F. Davis, Miss B. B. Britton, Lt. Cmdr. R. N. Colwell, Lt. J. W. Hallstead (USN), Mr. R. H. Moyer, Dr. L. O. Quam, Dr. R. B. Withrow, Dr. H. A. Rodenhiser, and Mr. H. J. Keegan. At this meeting, a National Research Council memo, dated May 1, 1952, entitled, "Guide to photography and field work" was prepared by Lt. Cmdr. Colwell, Mr. Keegan, and Dr. Rodenhiser on flight instructions, spectrophotometry, and plant culture, respectively.

May 7, 1952. Initial spectral directional reflectance curves were made on some of Dr. Rodenhiser's young wheat plants, that were grown in pots under controlled conditions at Beltsville, Maryland, which he brought to the NBS for measurement.

May 15, 16, and 26, 1952. Additional specimens of cut wheat leaves and pure spore were brought from Beltsville for measurement at the NBS.

May 29, 1952. Lt. Cmdr. Colwell brought to the NBS for measurement, specimens of diseased and rust-resisting field-grown wheat plants flown to Washington, D. C. from Stillwater, Oklahoma. Spectrophotometric curves of the leaves of specimens of Westar wheat having high and low rust severity were given to Lt. Cmdr. Colwell after the completion of the measurements that day.

June 3, 1952. Additional specimens of cut wheat leaves from inoculated plants and specimens of pure stem and leaf rust were brought to the NBS for measurement by Dr. Rodenhiser and Dr. C. V. Lowther.

September 3, 1952. Spectrophotometric curves of the heads and stalks of high and low rust severity Westar wheat plants were given to Lt. Cmdr. Colwell for his talk before the Optics Division, Armed Services Research and Development Board.

September 5, 1952. Lt. Cmdr. Colwell informally presented the data obtained on May 29, 1952, together with photographs of fields of growing wheat, to the members of the Seventh Congress of the International Society of Photogrammetry, sponsored by the American Society of Photogrammetry, at the Shoreham Hotel, Washington, D. C.

September 7, 1952. Lt. Cmdr. Colwell presented the same material to the NRC Committee on Plant and Crop Ecology, Dr. R. E. Cleland, Chairman, at Cornell University, Ithaca, N. Y.

December 1, 1952. Mr. Keegan was thanked by the Executive Secretary, Dr. E. F. Davis, by letter, for the "spectral analysis of the plant materials from Beltsville, and those involved in photographic work done this summer in Oklahoma". The whole matter was dropped temporarily with the following statement "while the resulting interpretation by the Subcommittee on Crop Geography and Vegetation Analysis was not altogether conclusive, it has given a good indication of the present limitations in this field, and the value of continuing research".

January 16, 1953. H. J. Keegan presented a paper at the Nineteenth annual meeting of the American Society of Photogrammetry on the "Use of reflection spectra for photointerpretation purposes" by H. J. Keegan and J. C. Schleter. The abstract of this paper was published in Photogrammetric Engineering XIX, 107 (1953).

January 30, 1953. Cmdr. L. W. Keith, Officer in charge, U. S. Naval Photographic Interpretation Center (U. S. Naval Receiving Station, Washington 25, D. C.), issued Report No. 102-53 "Aerial photographic interpretation of diseased and healthy cereal crops". (This report contains a graph of the spectral directional reflectance of the leaves of Westar based on NBS measurements but with wrong labeling of the wavelength scale).

June, 1953. In the issue of Photogrammetric Engineering (vol. XIX, 468 to 472) there appeared a "Report of unclassified military terrain studies section" by Page E. Truesdell, U. S. Navy Photographic Interpretation Center, Washington, D. C. This report was a part of the report of the Photo Interpretation Committee of the American Society of Photogrammetry. This paper contained the spectral directional reflectance curves of the leaves of Westar wheat plants, having high and low rust severity, that had been given to Lt. Cmdr. Colwell on May 29, 1952. The wrongly labeled graph from the Keith report was used for this illustration. The error was drawn to the attention of Mr. Truesdell by telephone on August 17, 1953, who arranged to have the corrected graph published (Photogrammetric Engineering, XIX, 851; December, 1953).

November 20, 1953. At a closed meeting in the Pentagon, Dr. Colwell again presented the series of photographs which were taken over Stillwater, Oklahoma, on May 27 or 28, 1952, Langdon, North Dakota, on August 14, 1952, and over Davis, California, in the fall of 1953.

January 19, 1954. Drs. Colwell and Davis brought specimens of diseased and non-diseased rye plants to the NBS for spectrophotometric measurements

to see if rye plants infected with rust behaved in the same way as wheat plants infected with rust.

March 12, 1954. Messrs. W. Paul Brandenburg and H. J. Keegan met with Dr. Davis in his offices in the Dupont Circle Building, Washington, D. C. to discuss the continuation of the work of the subcommittee on Crop Geography and Vegetation Analysis, by Dr. Colwell, Associate Professor of Forestry, University of California, Berkeley, California.

March 31, 1954. The Committee on Plant and Crop Ecology of the National Research Council was terminated.

May 26, 1954. Dr. Colwell agreed to continue his studies of this method of photointerpretation with support by WADC.

August 19, 1954. Dr. Colwell presented his aerial photographs taken with color, black and white, infrared, and camouflage detecting films at a meeting at the NBS. Those present: Messrs. Brandenburg, Jacocks, and Warren of WADC; Dr. Judd, Messrs. Keegan, Schleter, and Denne of NBS.

December 31, 1954. A looseleaf notebook containing the pre-publication draft of a paper entitled "The identification of cereal crop diseases on aerial photographs", by Dr. R. N. Colwell was received.

May 4, 1955. The notebook and pre-publication paper by Dr. Colwell, received at the NBS December 31, 1954, was returned to him at his request.

March 27, 1956. Dr. Colwell gave Mr. Keegan a "ditto" copy of his paper "Determining the prevalence of certain cereal crop diseases by means of aerial photography" for review.